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INFRARED SEARCH FOR YOUNG STARS IN HI HIGH-VELOCITY CLOUDS

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ABSTRACT

We have searched the IRAS Point Source Catalog and HIRES maps for young stellar objects (YSOs) in the direction of five HI high-velocity clouds (HVCs). In agreement with optical searches in the halo, no evidence was found for extensive star-forming activity inside the high-latitude HVCs. Specifically, we have found no signs of star formation or YSOs in the direction of the A IV cloud or in the very-high-velocity clouds HVC 110-7-465 and HVC 114-10-440. We have identified only one young star in the direction of the M I.1 cloud, which shows almost perfect alignment with a knot of HI emission. Because of the small number of early-type stars observed in the halo, the probability for such a positional coincidence is low; thus, this young star appears to be physically associated with the M I.1 cloud. We have also identified a good YSO candidate in the HI shell-like structure observed in the core region of the low-latitude cloud complex H (HVC 131+1-200). This region could be a supernova remnant with several other YSO candidates formed along the shock front produced by the explosion.

In agreement with recent theoretical estimates, these results point to a low but significant star-formation rate in intermediate and high Galactic latitude HVCs. For M I.1 in particular, we estimate that the efficiency of the star-formation process is $M(\mathrm{YSO})/M(\mathrm{HI}) \gtrsim 10^{-4} - 10^{-3}$ by mass. Such efficiency is sufficient to account for (a) the existence of the few young blue stars whose ages imply that they were born in the Galactic halo, and (b) the nonprimordial metallicities inferred for some HVCs if their metal content proves to be low.

Subject headings: Galaxy: halo — infrared: stars — stars: formation

1. Introduction

Most Galactic neutral hydrogen (HI) moves at velocities below about 100 km s^{-1} relative to the Local Standard of Rest (Heiles & Habing 1974). Nevertheless, Muller, Oort, & Raimond (1963) discovered HI clouds that move with velocities exceeding 100 km s^{-1}, too large to be explained by differential Galactic rotation. Many of these high-velocity clouds (HVCs) are located at intermediate and high Galactic latitudes (Giovanelli, Verschuur, & Cram 1973; Mathewson, Schwarz, & Murray 1977; Wakker 1991; Wakker & van Woerden 1991; van Woerden 1993) and do not appear to have any connection with the gas in the Galactic disk. Their origin is still unclear, mainly because the distances to the individual complexes are not known in most cases. (See Wakker et al. [1996] for a thorough review of HVC formation scenarios following an attempt to constrain the distance of two such clouds.)

Maps of the brightest HVC complexes have revealed the existence of fine structure at 10 arcmin resolution, which was further resolved into high-density cloud cores at 1 arcmin resolution (Wakker 1990; Wakker & Schwarz 1991, hereafter WS). The HI column densities in these cores are estimated to be several times 10^{20} cm^{-2} and their temperatures are generally between 30 and 300 K. Such conditions make the HVC cores possible sites of star formation. Indeed, based on estimates of core collision timescales, core masses, and Jeans masses, Dyson & Hartquist (1983) predicted substantial rates of star formation: up to 1000 early-type stars observable at any time in about 10% of all HVCs. In contrast, optical observations have not detected any associated stars or star clusters. Unlike the dense cores of molecular cloud complexes in the Galactic disk, the HVC cores do not appear to be active sites of star formation.

Theoretical predictions for star formation rates in the HVCs have been recently revised by Christodoulou, Tohline, & Keenan (1997). Based on the latest high-resolution radio observations, they estimate that HVCs should not be sites of significant star formation. This result agrees with the observations but poses yet another problem for the theory of star formation: A number of young blue stars are observed at high Galactic latitudes and at large distances from the Galactic disk (Keenan et al. 1986, 1995; Conlon 1993; Little et al. 1995; Hambly et al. 1996). One explanation is that these stars were formed in the disk and were later ejected into the halo because of stellar dynamical interactions in clusters, or because of supernovae explosions in binaries (Leonard 1993 and references therein). For about ten B-type halo stars, however, the inferred ages are substantially shorter than the travel times from the disk to their present locations, supporting the alternative proposal that some stars do form in the Galactic halo.

This problem could be solved if there were star formation in HVCs even at quite low rates. Such rates would be in agreement with both optical and HI observations, and with the presence of just a few unusual young stars at high Galactic latitudes. In addition, low rates would be in accord with the nonprimordial metallicities observed in some HVCs (van Woerden 1993) and especially with metal abundances whose origin cannot be attributed to alternative mechanisms (e.g., galactic fountains; Sembach 1995). These possibilities justify an attempt to find observational evidence for

star formation in HVCs.

Collapsing cloud cores and young stellar objects (YSOs) with gas column densities of at least a few times 10^{20} cm^{-2} and standard dust properties are detectable at infrared wavelengths by the IRAS satellite (Boulanger, Baud, & van Albada 1985). In fact, the spatial resolutions of recent HI observations (WS) and of IRAS maps are comparable ($\sim$ 1 arcmin), which greatly simplifies their comparison. Wakker & Boulanger (1986) searched for infrared emission at 100 μm in the direction of two HVCs, but this search produced a negative result. They found no correlation between the HI and 100 μm emission, a result that they attributed to either very cold dust ($\lesssim$ 20 K) or to a dust-to-gas ratio smaller than the standard interstellar value. Wakker & Boulanger did not consider IRAS maps at other wavelengths, or information about YSO candidates available in selected regions from the IRAS Point Source Catalog (PSC). In this work we have extended the search to five HVCs (A IV, M I.1, complex H, HVC 110-7-465, and HVC 114-10-440) recently observed in HI by WS, utilizing both the PSC and HIRES maps (HIgh RESolution IRAS images) at all four IRAS wavelengths (12, 25, 60, and 100 μm). Our searching procedure and the results for each HVC are described in § 2. In § 3 we summarize our findings.

2. The Search for YSOs in the IRAS Database

2.1. The Search in the IRAS PSC

WS observed the HI emission from several HVCs with 1 arcmin spatial resolution and 1 km s^{-1} velocity resolution. We have used their maps to positionally constrain our search for YSOs. The covered areas are the smallest rectangles which fully include the regions of observed HI emission. Their typical sizes are about 1°. The first step was to find all IRAS point sources in the corresponding directions; this search resulted in 21 sources. For each source, we can distinguish whether it is a YSO or a late-type star by using the infrared colors based on their four IRAS fluxes: Late-type stars are much brighter at the two shorter wavelengths than at the two longer wavelengths, while the opposite is true for young stars, star-forming regions, and galaxies (Ivezić & Elitzur 1996). However, this criterion can be safely applied only if the source has good-quality flux measurements (quality 3; see IRAS Explanatory Supplement). In addition to excluding all bona fide late-type stars, we also eliminated all sources that do not show positional coincidence with the structures seen in HI emission. The remaining 8 YSO candidates are listed in Table 1. For these sources, we have obtained HIRES images at all four IRAS wavelengths. The location of one additional IR source (not listed in Table 1 since it is not in the PSC) in the M I.1 cloud and the locations of three sources in complex H are also marked in Fig. 1 that depicts the corresponding HI emission maps kindly supplied by B. Wakker. These sources are the best candidates for embedded YSOs in the corresponding clouds. We proceed to discuss the results for each cloud separately.

Table 1:

IRAS PSC YSO Candidates Toward HI HVCs

HVC (1)	IRAS Source (2)	RA (3)	Dec (4)	F_{12} (5)	F_{25} (6)	F_{60} (7)	F_{100} (8)	YSO? (9)
M I.1	11235+4300	$11^h\ 23^m\ 31^s$	$+43^\circ\ 0'\ 0''$	0.27 (3)	0.25 (1)	0.53 (1)	1.18 (1)	No
A IV	09059+6227	$9^h\ 5^m\ 57^s$	$+62^\circ\ 27'\ 4''$	0.25 (1)	0.25 (1)	1.71 (3)	4.99 (3)	No
H	01572+6248	$1^h\ 57^m\ 14^s$	$+62^\circ\ 48'\ 1''$	0.25 (1)	0.25 (1)	0.64 (1)	5.55 (1)	Yes
H	01588+6219	$1^h\ 58^m\ 50^s$	$+62^\circ\ 19'\ 30''$	0.26 (3)	0.25 (1)	0.57 (1)	24.1 (1)	Yes
H	02020+6247	$2^h\ 2^m\ 1^s$	$+62^\circ\ 47'\ 40''$	0.37 (1)	0.25 (1)	1.66 (3)	5.84 (3)	Yes
H	02021+6228	$2^h\ 2^m\ 11^s$	$+62^\circ\ 28'\ 12''$	0.38 (3)	0.25 (1)	0.40 (1)	5.11 (1)	Yes
H	02022+6236	$2^h\ 2^m\ 16^s$	$+62^\circ\ 36'\ 10''$	0.69 (3)	0.26 (1)	0.45 (1)	6.33 (1)	Yes
114-10-440	23486+5103	$23^h\ 48^m\ 38^s$	$+51^\circ\ 3'\ 45''$	0.41 (3)	0.28 (1)	0.40 (1)	1.45 (1)	No

(1) HVC name.
(2) IRAS source name.
(3,4) Right Ascension and Declination (epoch 1950).
(5-8) Fluxes in Jy at the four IRAS wavelengths; flux qualities are listed in parentheses
(3: very good, 2: good, 1: upper limit).
(9) Our best determination of the YSO nature for each source, based on analysis of HIRES images.

2.2. Cloud M I.1

Cloud M I.1, one of the two brightest regions in complex M, contains five embedded HI cores (Fig. 1c in WS). An upper limit to the distance of the neighboring M II-M III region, $d \approx 5$ kpc, has been determined from absorption measurements in the direction of a background star (Danly, Albert, & Kuntz 1993; Keenan et al. 1995). We found one point source, IRAS 11235+4300, in the direction of M I.1. The four HIRES maps, centered on this source, are shown in Fig. 2. IRAS 11235+4300 (HD 99327) is barely visible in the 12 and 25 μm maps and nonexistent at 60 and 100 μm, indicating that it is a late-type star, an identification also supported by its spectral type K0. The large fluxes at 60 and 100 μm listed for this source in Table 1 are probably caused by imperfections in the correction procedure for the background cirrus emission (Ivezić & Elitzur 1995).

On the other hand, there is in Fig. 2 a sign of point-like very cold emission indicative of a YSO at RA=$11^h\ 23^m 51 \pm 2^s$ and Dec=$43^\circ 21.3 \pm 0.5'$ corresponding to the position just below the upper edge, slightly shifted to the left from the image center. This emission appears as a faint source at 60 μm (just above the noise level) and as a quite bright knot at 100 μm. Interestingly, the knot coincides precisely with a peak of HI emission (Fig. 1a). QSO 1123+434 (RA=11^h $23^m 49.41^s$, Dec=$43^\circ 26' 7.4''$) is in the vicinity of the knot as well, but it does not coincide with the

region of the infrared emission.

Assuming a cloud with constant temperature T and standard dust optical properties, the temperature of the emitting dust can be estimated from the ratio F_{100}/F_{60} of the 100 to 60 μm fluxes that is obtained from the corresponding images. For the bright knot at 100 μm, we find that $F_{100}/F_{60} \approx 2.5$ and $T = 96/\ln(10F_{100}/F_{60}) \approx 30$ K. For a standard dust-to-gas ratio and measured total HI column density of $\mathcal{N} = 4.36\times10^{20}$ cm^{-2} (core #4 in Table 2 of WS; see also their Table 1), the intensity of the resolved emission at 100 μm would be $I_{100} = 4\times10^{-17}(\mathcal{N}/\mathrm{cm}^{-2})\exp(-144/T) \approx 140$ MJy sr^{-1}. Since the measured peak intensity is about 1 MJy sr^{-1}, and the size of the IRAS point spread function (PSF) at 100 μm is $\sim$1 arcmin, the angular size of the emitting region is estimated to be about 5 arcsec. Assuming an upper limit of 5 kpc for the cloud distance, this angular size corresponds to an upper limit of 10^{17} cm, comparable to expected collapsing-core sizes. Thus, it is conceivable that the source at RA=11^h $23^m51 \pm 2^s$ and Dec=$43°21.3 \pm 0.5'$ is a YSO physically associated with cloud core #4 in HVC M I.1.

2.3. Cloud A IV

Cloud A IV is the brightest region in complex A (Wakker & van Woerden 1991) and shows filamentary structures in HI (Fig. 1a in WS). We found one point source in this region, IRAS 09059+6227, that can be identified in all four panels shown in Fig. 3. Its brightness increases rapidly with wavelength indicating that the source is not a late-type star. Cross-referencing of various catalogs showed that this source positionally coincides with the galaxy UGC 4803 (RA=9^h $5^m56.9^s$, Dec=$62°26'58''$), also observed by Davis & Seaquist (1983). It seems that IRAS 09059+6227 is a galaxy projected on the sky near the edge of A IV.

2.4. Complex H

Unlike complexes A and M, the extended complex H (diameter 20°) is centered near the Galactic plane. The large-scale velocity field suggests the presence of an expanding shell with velocity $v = 70$ km s^{-1} (Fig. 1i in Wakker & van Woerden 1991). The origin of this cloud is uncertain. WS discuss the possibility of a dense high-velocity cloud impacting the disk from the side, creating a shock front. Alternatively, the expanding shell geometry could be indicative of a supernova remnant.

Table 1 lists five sources that could be associated with the core of complex H (HVC 131+1-200), although only three of them (IRAS 01572+6248, 01588+6219, and 02021+6228; Fig. 1b) show good positional coincidence with the HI shell structure observed in the central region of the complex (see also Fig. 1e in WS). IRAS 01572+6248 is located at the center of the 60 and 100 μm panels shown in Fig. 4. Part of the shell outline can be seen in the lower half of the same

panels, and its position and size roughly correspond to the inner shell observed in HI emission. Note that there is an offset between the center positions: from IRAS maps we get RA=1^h 58^m and Dec=$62°31'$, while the center position from the HI maps is RA=1^h 58^m 30^s and Dec=$62°34'$. The difference is about 3 arcmin or 3 FWHM of the PSF.

The close correspondence between the observed HI shell structure and the infrared maps makes the association of IRAS 01572+6248 with complex H very likely. Emission from this source increases toward long wavelengths indicating a YSO. Several other blobs can be seen along the shell's edge in the 100 μm map and their emission also increases with wavelength. Unfortunately, further analysis that could provide more clues about their nature is hampered by their weak emission which is not much stronger than the noise level. Thus, the detection of these sources remains tentative.

We have repeated the analysis of § 2.2 for the three sources whose positions coincide with the HI shell in the core of complex H (Fig. 1b). In all cases, we find from the images that $F_{100}/F_{60} \approx 2.0$ implying a temperature for the emitting dust of about 32 K. For a standard dust-to-gas ratio and for total HI column densities of $\mathcal{N}$ = (1.3-2.6)$\times10^{20}$ cm^{-2}, the intensities of the resolved emission at 100 μm would range between 60 and 120 MJy sr^{-1}. Since the measured peak intensities are between 3 and 6 MJy sr^{-1}, respectively, the angular sizes of the emitting regions are all estimated to be about 0.22 arcmin. With a lower limit on the cloud distance of about 5 kpc (Wakker & van Woerden 1997), we derive a lower limit of 3×10^{17} cm for the sizes of these regions. This value is at least three times larger than the size of the YSO found in cloud M I.1. A more precise comparison cannot be made because of the uncertainty in the determinations of the distances of the two HVCs.

2.5. HVC 110-7-465 and HVC 114-10-440

These two very-high-velocity clouds are only 5° apart in the sky and have similar structures (Figs. 1f and 1h in WS). Well-defined gradients in the velocity fields indicate that both clouds are rotating. In the region outlined by HI emission from these clouds, we found only one source, IRAS 23486+5103. It has a very good positional coincidence with the peak of the HI emission in HVC 114-10-440, and at first it appeared to be the best candidate for a YSO associated with an HVC. Unfortunately, inspection of HIRES maps shows that this source is a late-type star (HD 223626) because the intensity of its emission decreases with wavelength, and its spectral type is listed as K2. An increase in fluxes listed in Table 1 from 60 to 100 μm is probably due to imperfections in the correction procedure for the background cirrus emission, since it is not corroborated by the detailed images.

HIRES maps of the region toward these two clouds show hints of two more YSOs based on their stronger emission at 60 and 100 μm relative to the shorter wavelengths. These sources are located quite far from the regions of elevated HI column density and their apparent association

with these HVCs is probably just a projection effect. Thus, our search for embedded YSOs has produced negative results in the cases of HVC 110-7-465 and HVC 114-10-440.

3. Summary and Conclusions

We have examined the infrared emission in the direction of five HVCs, searching the IRAS Point Source Catalog and the corresponding high-resolution images at all four IRAS wavelengths. We have found no evidence for extensive star-formation activity in any of the surveyed regions that show HI emission (WS). Yet, a low rate of star formation inside HVCs remains a possibility in light of the discovery of a few individual early-type stars. Specifically, one such star was found in the direction of the M I.1 cloud and it is quite possible that this star is embedded in the cloud (§ 2.2). In contrast, no early-type stars were found toward the A IV cloud (§ 2.3). The remaining five sources (one likely detection and four tentative YSO candidates) were found toward the inner shell structure in the low-latitude complex H (HVC 131+1-200) and they could have formed in the shock front created by a supernova explosion (§ 2.4). Finally, no YSOs were found toward the very-high-velocity clouds HVC 110-7-465 and HVC 114-10-440 (§ 2.5).

A low star-formation rate at intermediate and high Galactic latitudes, consistent with the single YSO found in M I.1, is in agreement with recent theoretical estimates (Christodoulou et al. 1997), showing that it is very difficult for a collisional mode of star formation to be excited in halo HVCs. The star-formation efficiency in M I.1 can be estimated as the fraction of the cloud's mass that is converted into a star: Using $d \leq 5$ kpc for the distance and $\mathcal{N} \approx 3{\times}10^{20}$ cm^{-2} for the HI column density of the densest cloud core with angular diameter 1°, we find from the equations of Christodoulou et al. (1997) a radius of $R \lesssim 44$ pc and a mass of $M(\mathrm{HI}\ ) \lesssim 10^4$ $\mathrm{M}_\odot$. Assuming then a mass of $M(\mathrm{YSO}) \sim 1 - 10$ $\mathrm{M}_\odot$ for the detected YSO, we find that $M(\mathrm{YSO})/M(\mathrm{HI}\ ) \gtrsim 10^{-4} - 10^{-3}$. Such efficiency can account for the observed nonprimordial metallicities (e.g., van Woerden 1993) only if they prove to be low and for the existence of ~ 10 young blue stars whose ages imply that they were born in the Galactic halo (e.g., Conlon 1993). These halo stars are not clearly projected toward HVC cores or regions of pronounced HI emission, and to further support the latter hypothesis it is important to examine whether they have had enough time to abandon their HVC birthplaces.

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FIGURE CAPTIONS

Fig. 1.— The locations of four YSO candidates probably embedded in the corresponding HVCs. The gray scale images are HI maps obtained by WS. A bar denotes an angular scale of 10 arcmin for both maps and the positions of the sources are indicated by open circles. (a) The YSO in M I.1 at RA=$11^h\ 23^m 51^s$ and Dec=$43°21.3'$ (see § 2.2). (b) Three IRAS PSC sources in complex H (see § 2.4).

Fig. 2.— HIRES images at four IRAS wavelengths (12, 25, 60, and 100 μm) in the direction of cloud M I.1. The $1° \times 1°$ images are centered on the source IRAS 11235+4300 at the coordinates listed in Table 1. The vertical bar next to the right edge of each panel shows the intensity scale in MJy sr^{-1}. The upper cut-off in each panel was set to 2 MJy sr^{-1} in order to emphasize the regions with low-level intensities.

Fig. 3.— As in Fig. 1, but in the direction of cloud A IV. The $1° \times 1°$ images are centered on the source IRAS 09059+6227 at the coordinates listed in Table 1.

Fig. 4.— As in Fig. 1, but in the direction of complex H. The $1° \times 1°$ images are centered on the source IRAS 01572+6248 at the coordinates listed in Table 1.

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